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Research Paper

Can spatial planning really mitigate carbon dioxide emissions in urban areas? A case study in Taipei, Taiwan

Szu-Hua Wang[a], Shu-Li Huang[b,*], Po-Ju Huang[b]

[a] Department of Urban Planning and Development Management, Chinese Culture University, 55 Hwa-Kang Rd., Yang-Ming-Shan, Taipei City, 11114, Taiwan
[b] Graduate Institute of Urban planning, National Taipei University, 151 University Rd., Sanshia District, New Taipei City, 23741, Taiwan

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ABSTRACT

Spatial planning plays an increasingly significant role in climate change mitigation by providing energy efficient settlements and promoting the utilization of renewable energy resources. However, the effect of urban spatial planning on spatial pattern of carbon dioxide emissions in cities is rarely discussed. The relationships between the changes in urban zoning plans and carbon dioxide emissions of major economic sectors has yet to be investigated on a scale smaller than an entire city. Using the Taipei metropolitan area as a case study, this study hypothesizes that: (1) carbon dioxide emissions have a spatial dimension within the city due mainly to the heterogeneous nature of land use activities and urbanization, and (2) changes in spatial planning can influence the urban form, and consequentially affect carbon dioxide emissions through changes in traffic demand and energy consumption. A downscaling analysis approach was used to estimate carbon dioxide emissions of different sectors for each administrative district in the Taipei metropolitan area. The analytical results reveal that the total carbon dioxide emissions of the four sectors in the Taipei metropolitan area increased with the increases in the growth of urban planned zones during the period 1981–2011.The carbon dioxide emission increases were correlated with the distribution of land uses in each administrative district. A negative correlation was found between the population density and the *per-capita* carbon dioxide emissions in the transportation sector. The compact development and planning of urban transit systems are believed to be the source of decreasing per-*capita* carbon dioxide emissions. While many studies have emphasized that spatial planning is important addressing climate change, this work demonstrates understanding the historic links between spatial planning and carbon dioxide is equally valuable.

1. Introduction

Although climate change is a global issue requiring top-down solutions based on international treaties, urban areas also play an increasing role in climate change mitigation (Rosenzweig, Solecki, Hammer, & Mehrotra, 2010). As the result of urbanization, the spatial organization of land use activities and transport systems are closely interrelated and in turn affect greenhouse gas (GHG) emissions in urban areas (Bulkeley, 2006; Marcotullio, Sarzynski, Albrecht, Schulz, & Garcia, 2016). The spatial organization of human settlements — including urban form — needs to be understood in order to formulate efficient and effective strategies for mitigating GHG emissions. The planning and design of the spatial pattern of urban development must encourage sustainable transportation such as public transportation options, cycling and walking, and reduced use of vehicles. In addition, compact and higher urban densities (lower surface-to-volume ratios) are considered much more energy efficient than low density buildings (Wende, Huelsmann, Marty, Penn-Bressel, & Bobylev, 2010).

Many researchers have investigated the empirical relationships between urbanization and CO_2 emissions and found positive correlations (Cole & Neumayer, 2004; Poumanyvong & Kaneko, 2010; York, Rosa, & Dietz, 2003). An analysis of 88 developing countries during the period 1875–2003 identified an inverted U-shaped relationship between urbanization and CO_2 emissions, with a positive correlation between urbanization and CO_2 emissions existing for less urbanized countries (Martinez-Zarzoso & Maruotti, 2011). Sardorsky (2014) found that urbanization has a positive and statistically significant impact on CO_2 emissions in emerging economies. Ponce de Leon Barido & Marshall (2014) examined the influence of strong national environmental policies in higher income nations. Cities in high income nations with strong environmental policies not unexpectedly showed reduced CO_2 emissions.

Spatial planning can help achieve a low-carbon future by promoting new technologies to create new urban forms (Crawford & French,

* Corresponding author.
E-mail addresses: wsh4@ulive.pccu.edu.tw (S.-H. Wang), shuli@mail.ntpu.edu.tw (S.-L. Huang), pajuhuang@gmail.com (P.-J. Huang).

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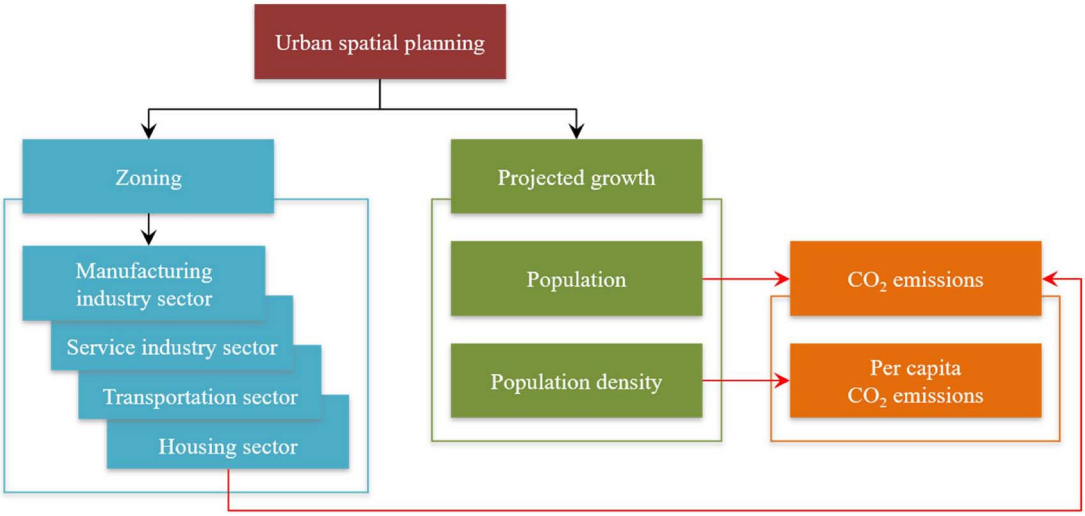


Fig. 1. The conceptual framework of urban spatial planning and CO_2 emissions.

2008). Spatial planning plays an increasingly important role in achieving climate change targets by helping mitigate CO_2 emissions through the rational allocation of land uses to improve energy efficiency and through protection of green infrastructure (Bulkeley, 2006; Campbell, 2006; Wende et al., 2010). In addition, spatial planning contributes to the development of integrated strategies, and also functions as a mechanism to implement local and regional strategies (Biesbroek, Swart, & van der Knaap, 2009). From neighborhood plans to metropolitan spatial development frameworks, spatial planning has helped determine the character of cities, significantly affecting urban system metabolism and resource use. The Intergovernmental Panel on Climate Change (IPCC) included a chapter on "Human Settlement, Infrastructure, and Spatial Planning" in Working Group III of IPCC AR5 in 2014 (Seto et al., 2014). This chapter reviewed and discussed spatial planning strategies to mitigate CO_2 emissions from different geographic scales to reduce urban sprawl and energy consumption in transportation.

Given the contribution by cities to CO_2 emissions, consensus is building around the role of cities in reducing emissions and reducing the impact of climate change. From a spatial planning perspective, urban form can have potentially significant impacts on energy use, resource consumption and the ability of a region to mitigate climate change (Blanco, McCarney, Oarnell, Schmidt, & Seto, 2011). Governments, authorities and individuals worldwide have deliberately planned cities to determine their character, and responded to the stimuli of demographic changes with associated demand for housing, economic opportunities and institutional changes. Spatial planning frameworks can modify urban form to mitigate climate change. Important measures to reduce CO_2 emissions include reducing traffic demand and energy consumption. Although spatial planning is claiming an increasingly important role in climate change mitigation by providing energy-efficient settlements and promoting the utilization of renewable energy resources, the impact of historic urban spatial planning activities on the current spatial patterns of CO_2 emissions in the cities has rarely been discussed. The relationships between the changes in urban zoning plans and the CO_2 emissions of major sectors has also not been widely investigated, especially on a scale smaller than a city.

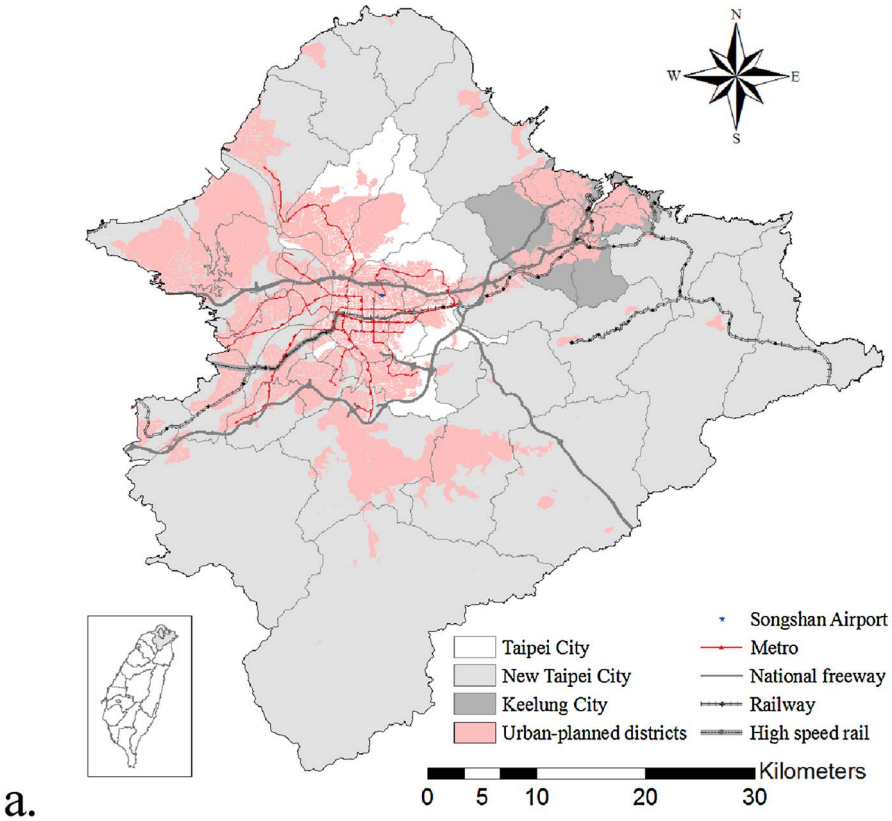
Using the Taipei metropolitan area as a case study, this study hypothesizes that: (1) CO_2 emissions have a spatial dimension within the city due mainly to the heterogeneous nature of land use activities and urbanization, and (2) spatial planning can influence the urban form, and consequentially affect CO_2 emissions through traffic demand and energy consumption (Section 2). Following the brief description of the study area (Section 3), Section 4 describes the calculation of CO_2 emissions in each administrative district within the Taipei metropolitan area through the downscaling of the city-level CO_2 emissions of each sector (manufacturing industry, transportation, service industry and housing). Section 5 analyzes the relations between CO_2 emissions and land use variables; the impact of spatial planning on the spatial dimensions of CO_2 emissions are also discussed, and section 6 draws conclusions.

2. Framework

Urbanization creates enormous environmental change resulting from socioeconomic transformation in urban areas. Generally, urbanization is viewed as a phenomenon of the concentrated population in a specific area, as an intensive and high density land use of human settlement and land cover, and a series of interconnected processes and transitions of interactions between humans and their environment (Li, Sato, & Zhu, 2003; McIntyre, Knowles-Yánez, & Hope, 2000). Exploring the interrelationships between urbanization and the socio-ecological and technological components of urban areas can further understand how urbanization affected the spatial and temporal pattern of carbon emissions within and across cities (Romero-Lankao et al., 2014). Therefore, urbanization is related to demography, economy and infrastructure in a city (Li et al., 2003; Romero-Lankao et al., 2014).

Urbanization has also been identified as one of the main causes of increased CO_2 emissions (Martinez-Zarzoso & Maruotti, 2011; Sadorsky, 2014; Cetin & Ecevit, 2015). Urban spatial planning can influence the urban form, traffic demand and energy consumption, and thus affects CO_2 emissions. Moreover, CO_2 emissions have a spatial dimension within cities because of the heterogeneous nature of land use activities and urbanization. In order to investigate the relationships between the changes in urban zoning plans and the CO_2 emissions of major sectors on a scale smaller than a city, Fig. 1 illustrates the hypothesized framework of the effect of urban spatial planning on CO_2 emissions.

In Taiwan, urban spatial planning determines amounts and distributions of population and, at the same time, population density as shown in Fig. 1. Increases in population have been considered the most obvious direct phenomenon affecting CO_2 emissions in cities (Dietz & Rosa, 1997). Population growth is also a major factor causing the increase of CO_2 emissions in OECD countries (Hamilton & Turton, 2002). Sadorsky (2014) and Zhao & Wang (2015) formulated models to analyze the impacts of population on CO_2 emissions and discovered a clear positive linear relationship between population growth and CO_2 emissions. CO_2 emissions in many Asian countries, such as the Philippines, Malaysia, China and Japan, are concentrated in areas with



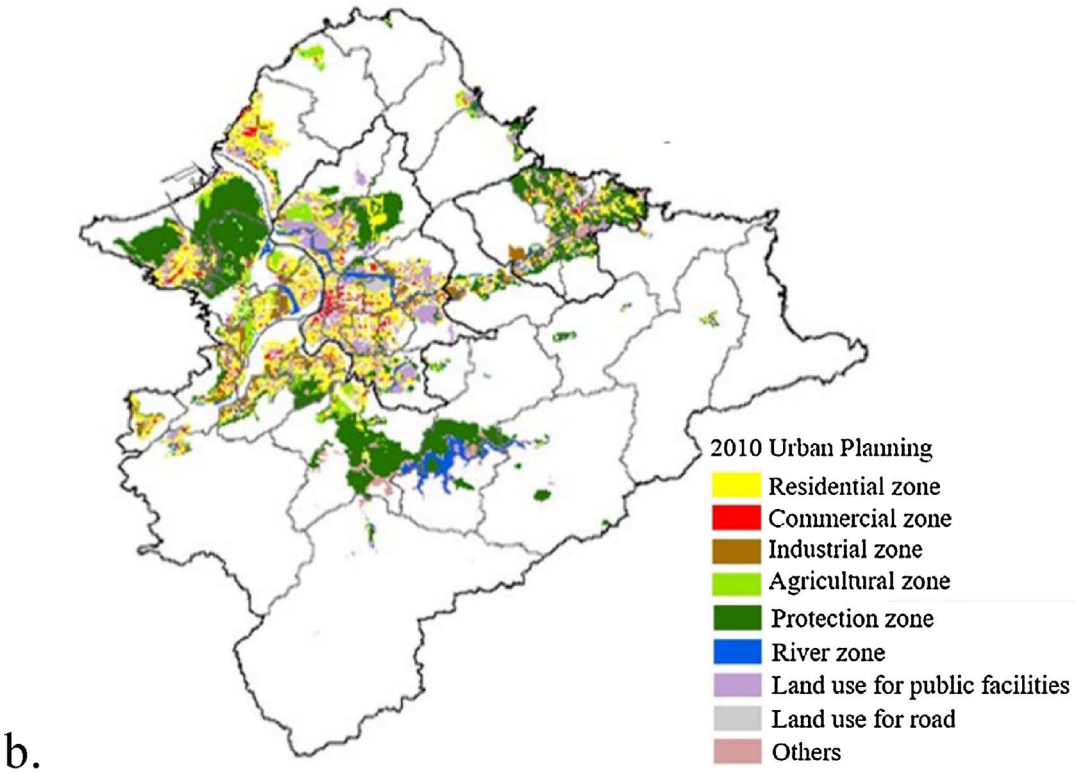


Fig. 2. Taipei metropolitan area: (a) Location; (b) Urban planning.
Source: Construction and Planning Agency Ministry of the Interior, 2010.

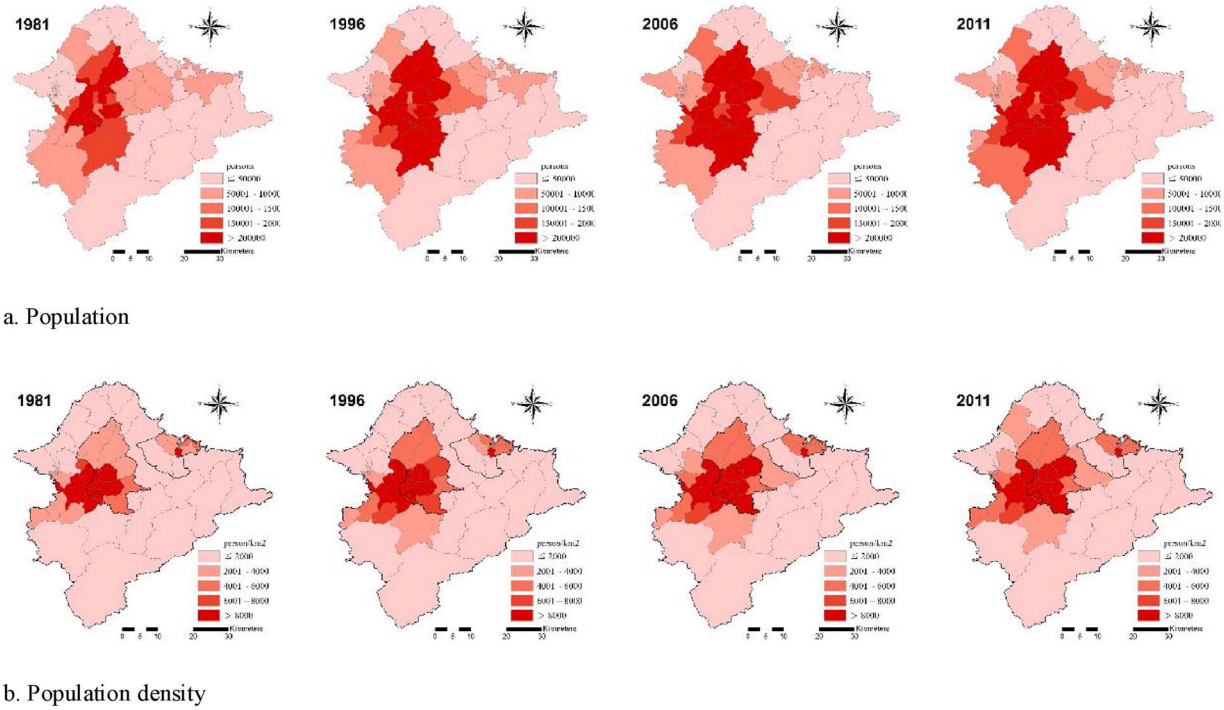


Fig. 3. The population and population density distribution maps of the Taipei metropolitan area.

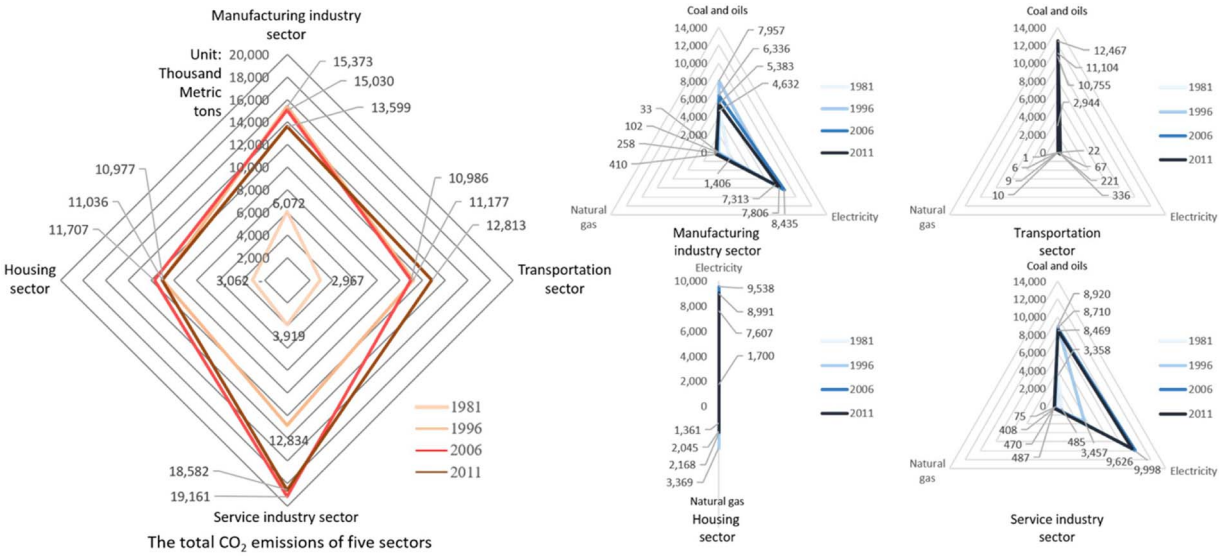
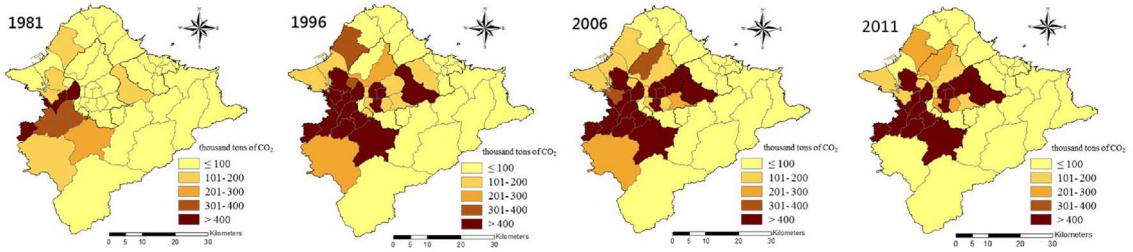


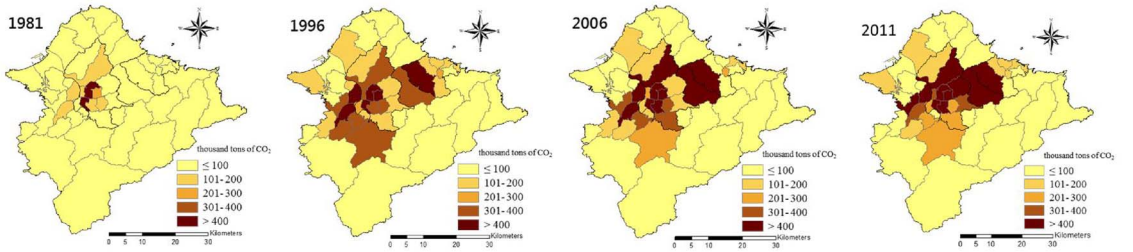
Fig. 4. The CO_2 emissions of the four sectors in the Taipei metropolitan area.

high population densities (Abesamis, Campos, & Castell, 2013;Begum, Sohag, Syed Abdullah, & Jaafar, 2015; Hossain, 2012; Zhang & Cheng, 2009). As well as total population, additional demographic variables such as population density and the rate of population growth also effect CO_2 emissions (Martinez-Zarzoso & Maruotti, 2011). Thus, the relationships between population and CO_2 emissions as well as the relationships between population density and *per-capita* CO_2 emissions should be analyzed separately.

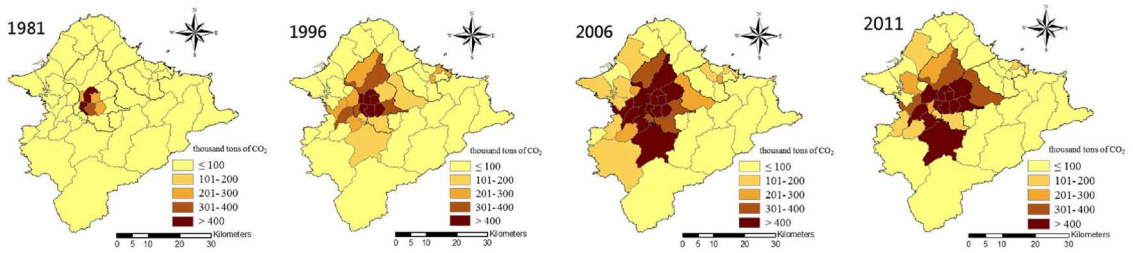
Land zoned for manufacturing industrial, service industrial or residential use is determined by Taiwan's zoning plans. Zoning plans may also affect the distribution of CO_2 emissions within the cities as shown in Fig. 1. Urbanization is related to economic growth thereby changing CO_2 emissions from different sectors (Abesamis et al., 2013; Cetin & Ecevit, 2015; Martinez-Zarzoso, 2008; Sadorsky, 2014; Seto et al., 2014). Barido & Marshall (2014) indicated that increasing economic activity correlates with urbanization and can increase energy consumption and CO_2 emissions. Hossain (2012) identified positive relationships between energy consumption, economic growth, urbanization and CO_2 emissions in Japan. Li et al. (2016) also discovered that economic growth and urbanization are the key determinants of CO_2 emissions in China. Different sectors are assumed to cause various amounts of CO_2 emissions depending on the areas zoned for their land uses in the administrative districts. To accommodate growth while prohibiting development in protected areas, urban spatial planning coordinates activities in different sectors and spatially allocates different land uses by regulating permitted activities in different zones (Huang & Wang, 2016). The designated areas and intensity permitted affect not only economic productivity, but also the amount and density of CO_2 emissions. Floor area and floor area ratio can be considered as the primary land use intensity drivers, which directly and indirectly



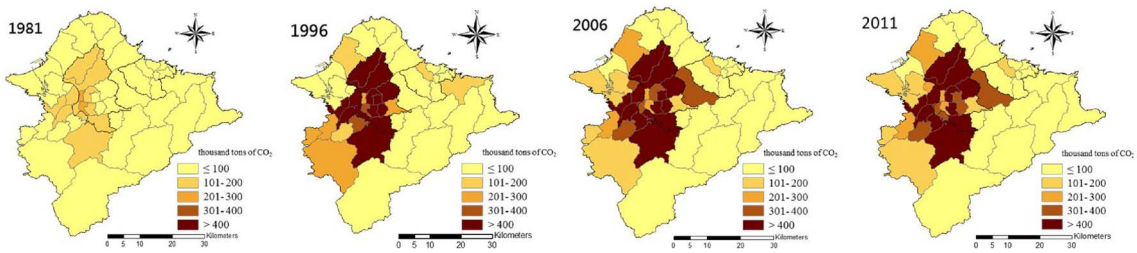
a. The CO_2 emissions of the manufacturing industry sector



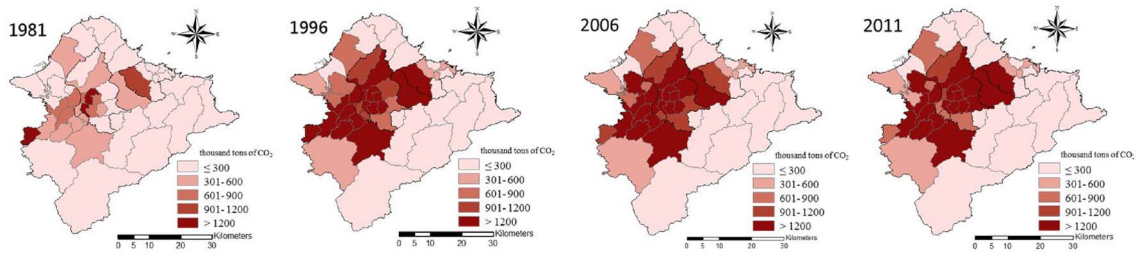
b. The CO_2 emissions of the transportation sector



c. The CO_2 emissions of the service industry sector



d. The CO_2 emissions of the housing sector



e. The total CO_2 emissions

Fig. 5. The results of the downscaling analysis in the Taipei metropolitan area.
Source: Wang, Huang, Lee, & Hsiao, 2016.

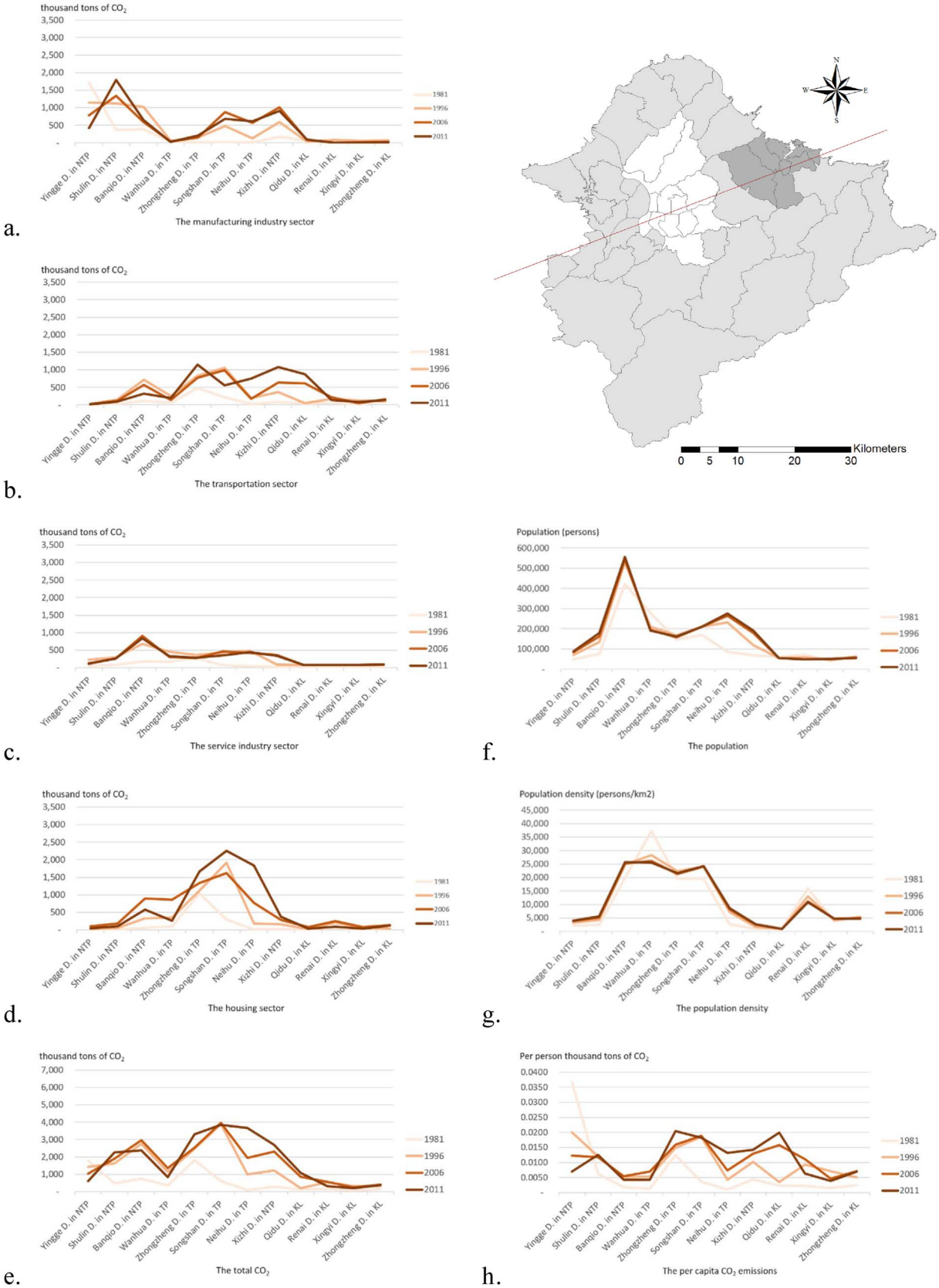
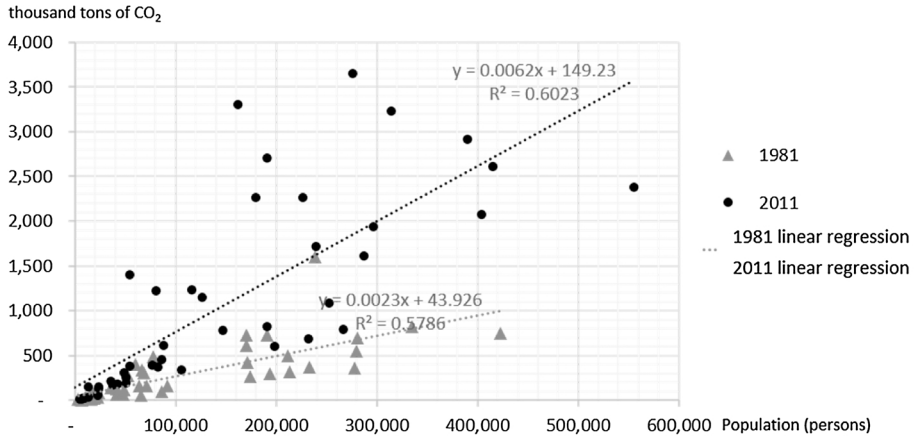
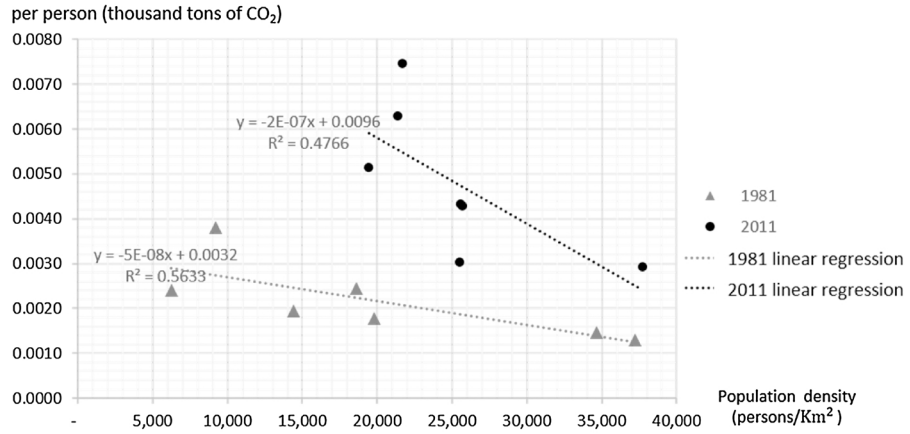


Fig. 6. The distributions of CO_2 emissions form the center of the Taipei metropolitan area to the periphery area.



a. The distribution of the population and its relationship with the CO_2 emissions



b. The distribution of the population density and its relationship with the per-capita CO_2 emissions in the high density districts

Fig. 7. The relationships between the CO_2 emissions and the urban development intensity in the Taipei metropolitan area.

influence thermal energy use as well as CO_2 emissions (Edenhofer et al., 2014; IPCC, 2014).

3. Study area

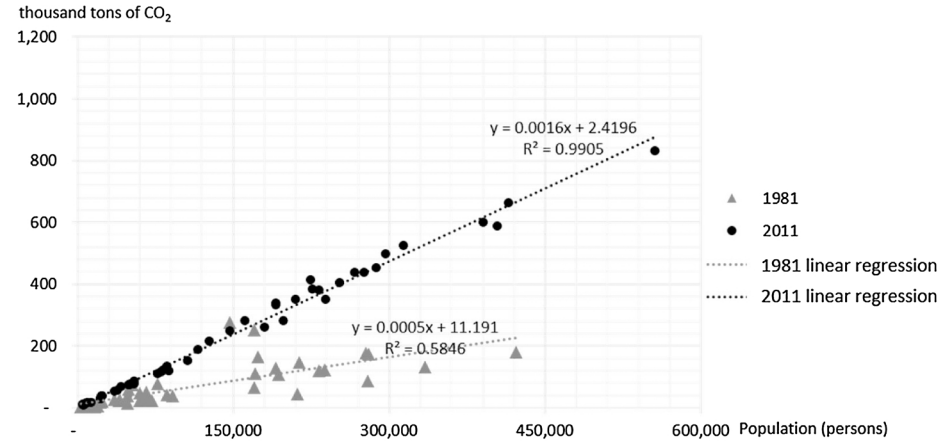
The rapid economic growth in Taiwan during the past decades has resulted in urban expansion. Nearly 80% of the total population in Taiwan now lives in urban areas. The Taipei metropolitan area, encompassing Taipei City, New Taipei City and Keelung City, is located in the northern part of Taiwan (Fig. 2a). It covers an area of approximately 2457 km^2, and has 48 administrative districts. The total population in the study area was approximately 7 million in 2016. The economy in the Taipei metropolitan area has transformed rapidly since 1970 from a rural economy to an industrialized and commercialized one. At present, the Taipei metropolitan area plays a significant role as the center of politics, economy, and culture of Taiwan.

Construction of buildings and streets in Taipei in the early 1900s was controlled by the Rules for Building Construction, which zoned land only for residential, schools and institutional uses, with no provision for commercial or industrial areas (Shih & Chen, 2010). The equal-width streets were planned as an undifferentiated street system. The Urban Planning Act and its implementation bylaw were enacted in 1936, integrating building control and land replotting into the Urban Planning Act. Land could be zoned for residential, commercial, institutional, industrial uses and protected areas. The Urban Planning Law was amended again in 1973 by the Regulation for Enforcement of Urban Planning Law. The Urban Planning Law has now has had 14 amendments in response to socioeconomic and political changes in Taiwan since 1939.

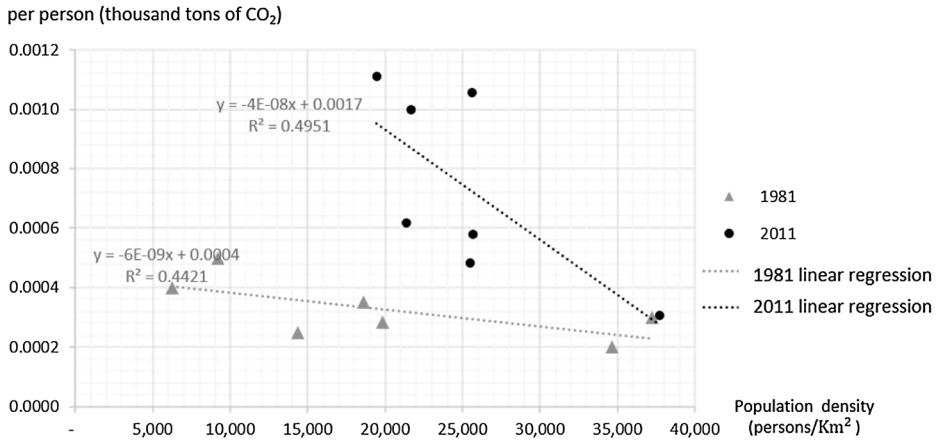
The urban planned zones in the Taipei metropolitan area now covers approximately 1592 km^2, including 120 km^2 of residential districts, 17 km^2 of commercial districts and 36 km^2 of industrial districts. The Metro system plays an important role in public urban transit. The built-up areas in the Taipei metropolitan area and its surrounding region, Taoyuan City, have increased by 130% from approximately 466 km^2 to 1071 km^2 from 1971 to 2006 (Huang, Wang, & Budd, 2009). Land use and land cover change in the study area generally took place near existing built-up areas or along major transportation corridors. New built-up lands in the Taipei area were also found to be strongly correlated with areas with high economic growth during the 1971–1990 period, while new built-up lands after 1990 were created in areas close to the urban centers (Wang & Chang, 2010). Urban planning and local economic development influenced the land use changes in the urban planned zones.

Fig. 2b shows urban spatial planning zoning map in the Taipei metropolitan area for 2010. The urban planned zones are concentrated in the center of the Taipei metropolitan area, covering most of the administrative districts in Taipei City and the western part of New Taipei City, as well as the administrative districts in the western part of Keelung City. The administrative districts with high population are mainly in the central part of the Taipei metropolitan area which are consistent with the urban zoning plan (Fig. 3). The administrative districts with higher population density were concentrated in the center of the Taipei metropolitan area in 1981 and spread out to the northeastern and southwestern parts of the study area during 1981–2011.

Fig. 7. (*continued*)



c. The relationship between the CO_2 emissions of the housing sector and the population in the high density districts



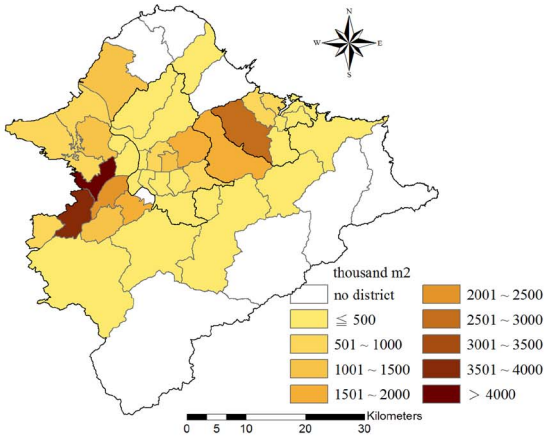
d. The relationships between the per-capita CO_2 emissions of the transportation sector and the population density in the high density districts

4. Downscaling analysis of CO_2 emissions of Taipei

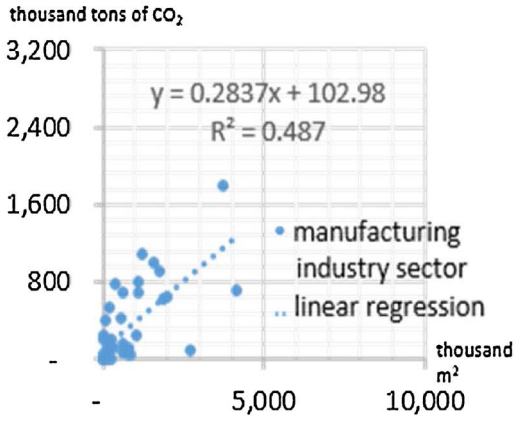
The Bureau of Energy of the Ministry of Economic Affairs (BOE) of Taiwan follows the "IPCC's Guidelines for National Greenhouse Gas Inventories" (IPCC, 2006), and has developed a national-level "Statistical Analysis of Taiwan Fuel Combustion Carbon Dioxide Emissions" (BOE, 2015) for use as the inventory and for the annual review of CO_2 emissions. On the basis of Taiwan's national inventory of CO_2 emissions, Lee et al. (2014) developed an integrated bottom-up system for estimating the urban CO_2 emissions of Taiwan's cities, providing a consistency check with top-down national estimates. Although the CO_2 emissions at the city level can monitor the effectiveness of top-down mitigation policies on cities as a whole, they cannot identify the spatial distribution of CO_2 emissions within the city.

To reveal the spatial difference in CO_2 emissions within cities in Taiwan, Wang et al. (2016) developed a downscaling analysis approach of urban CO_2 emissions based on the "IPCC Guidelines for National Greenhouse Gas Inventories" for the Taipei metropolitan area and Kaohsiung City. The downscaling analysis approach estimates the CO_2 emissions of each administrative district within the city and uses these figures to estimate CO_2 emissions of different sectors, including manufacturing industry, transportation, service industry and housing, from different energy consumption (e.g. electricity, natural gas and coal and oils). Three different scopes have been proposed for estimating CO_2 emissions: CO_2 emissions inside the study area boundary (Scope 1); CO_2 emissions inside the study boundary plus the CO_2 emissions from electricity use (Scope 2), and CO_2 emissions from the perspective of product life cycle based on CO_2 emissions from products produced from outside of the study boundary but consumed inside it (Scope 3) (Kennedy, Ramaswami, Carney, & Dhakal, 2009). Since stationary combustion and mobile combustion are the main sources of the spatial distribution of CO_2 emissions, this study estimates the Scope 2 CO_2 emissions of the Taipei metropolitan area. Appendix A presents the procedure and equations for the downscaling analysis of CO_2 emissions from city to each administrative district. According to Taiwan's statistics, such as "Industry, Commerce and Service Census", "The Report on Input-Output Tables", "Energy Balance Sheet of Taiwan" and "Taiwan Energy Statistics", energy consumptions are categorized into coal and different oils, electricity and natural gas. In order to avoid double counting problems, the items of energy use are categorized into coal and oils, natural gas and electricity. The CO_2 emissions of the manufacturing industry, transportation and service industry were calculated from the extracted energy expenditures of their registered addresses and the total quantity of their production outputs. The CO_2 emissions from the housing sector were estimated from housing energy expenditures.

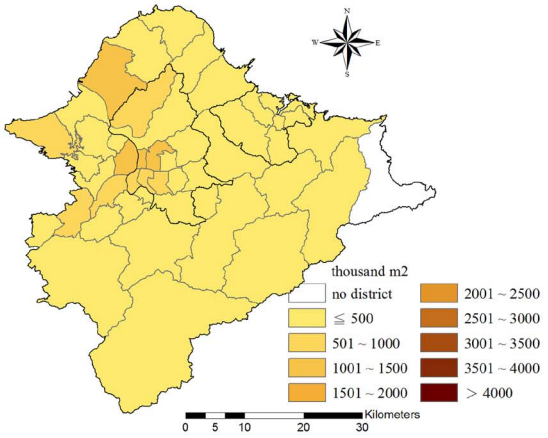
Our analysis indicates that the estimated total CO_2 emissions of the Taipei metropolitan area was 16,017 thousand tons in 1981. Fig. 4 illustrates the results of the estimated CO_2 emissions of the Taipei metropolitan area from the four sectors. The largest proportion of CO_2 emissions was generated from the manufacturing sector, 6,072 thousand metric tons in 1981, which accounts for 38% of the total CO_2



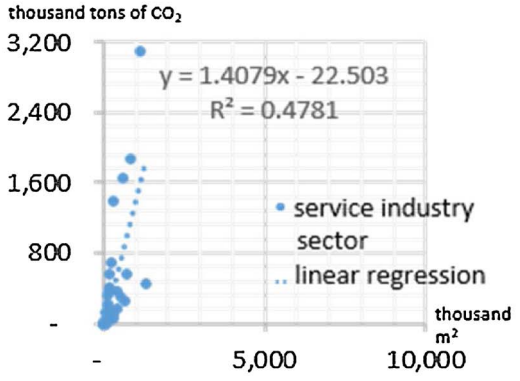
a. The distribution of the areas of the industrial zones in 2010



b. The relationships between the CO_2 emissions of the manufacturing industry sector in 2011 and the areas of the industrial zones 2010



c. The distribution of the areas of the commercial zones in 2010

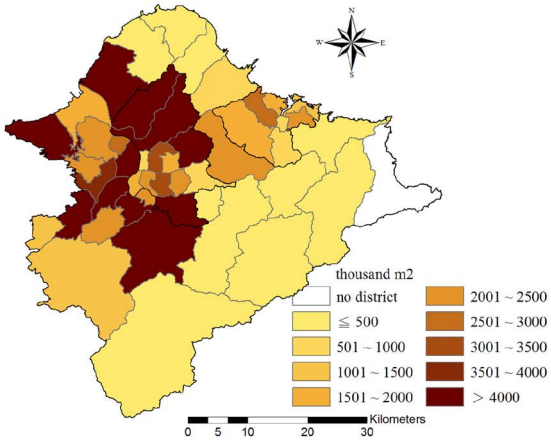


d. The relationships between the CO_2 emissions of the service industry sector in 2011 and the areas of the commercial zones in 2010

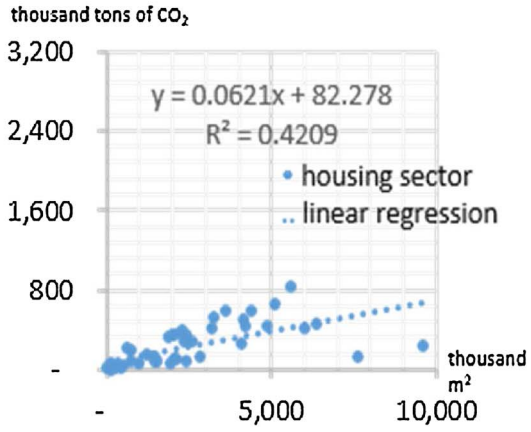
Fig. 8. The relationships between the CO_2 emissions and the land use types of the urban planned zones in the Taipei metropolitan area.

emissions. The CO_2 emissions from the manufacturing sector increased to 15,030 thousand metric tons in 2006, and then decreased to 13,599 thousand metric tons in 2011. The CO_2 emissions from service industry, housing sector and the transportation sector accounted for 24%, 19% and 19% (3,919, 3,062 and 2,967 thousand metric tons) of the total CO_2 emission in 1981 respectively. By 2011, the total CO_2 emissions of the Taipei metropolitan area had risen 250% reaching 56,029 thousand metric tons. The CO_2 emissions from the service industry sector increased significantly (18,582 thousand metric tons) and accounted for 33% of the total CO_2 emissions. The CO_2 emissions from the manufacturing sector, the transportation sector and the housing sector accounted for 24%, 23% and 20% (13,599, 12,813 and 11,036 thousand metric tons) of the total CO_2 emissions in 2011 respectively. The percentage of coal and oils used in the manufacturing industry sector declined from 76% to 40%, while the percentage of electricity had increased from 23% to 57% from 1981 to 2011. Most energy consumption in the transportation sector was attributed to coal and oils usage. The source of energy consumption in the service industry sector had changed from coal and oils (86%) in 1981 to electricity (52%) and coal and oils (46%). The main energy consumption of the housing sector also changed from electricity (56%) and natural gas (44%) in 1981 to electricity (81%) and natural gas (19%) in 2011.

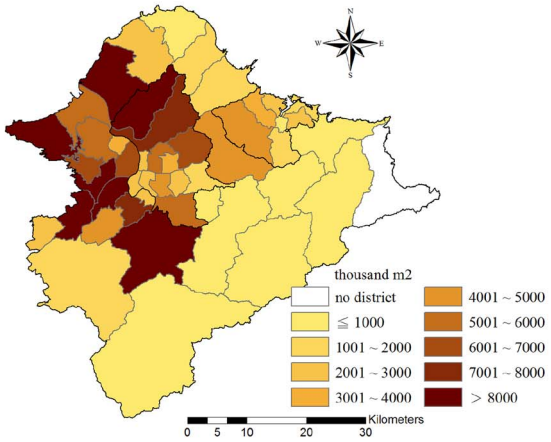
Fig. 5 shows the results of the estimated CO_2 emissions of each administrative district from different sectors. From 1981–2011, the CO_2 emissions of the manufacturing sector increased mainly in the west and center of the Taipei metropolitan area (Fig. 5a). About one third of the administrative districts in the study area emitted more than 300 thousand metric tons of CO_2 from their manufacturing industry in 2011. The CO_2 emissions of the transportation sector increased in the areas extending from the center to the eastern and western parts of the study area (Fig. 5b). Only 2 administrative districts emitted more than 300 thousand metric tons of CO_2 in 1981, rising to 12 administrative districts in 2011. The CO_2 emissions of the service industry sector and the housing sector increased mainly in Taipei City and in the districts adjacent to south and west of Taipei City (Fig. 5c and d). There were only 3 administrative districts which emitted more than 300 thousand metric tons of CO_2 from their service industry sector in 1981. This increased to 10 in 2011. More than 40% of the administrative districts emitted over 300 thousand metric tons of CO_2 in their housing sectors in 2011. Over this 30 year period, the CO_2 emissions from the manufacturing and service industries continued to rise and as a result the total CO_2 emissions increased mainly in the districts southwest and central of Taipei City, spreading from the center of Taipei City to the western part of New Taipei City and Keelung City (Fig. 5e). Only 4 administrative districts emitted more than 900 thousand metric tons of CO_2 in 1981, but this rose to more than 40% of administrative districts in 2011. In general, the spatial distributions of the estimated CO_2 emissions from 1981 to 2011 are similar to the spatial distribution of population and population density (Fig. 3).



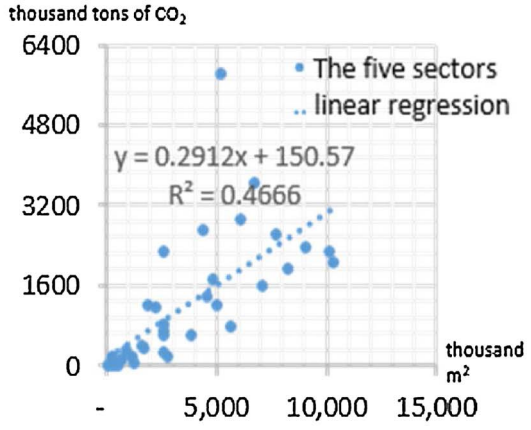
e. The distribution of the areas of the residential zones in 2010



f. The relationships between the CO_2 emissions of the housing sector in 2011 and the areas of the residential zones in 2010



g. The distribution of the total areas of the industrial zones, the commercial zones, the residential zones, the agricultural zones and the transportation lands in 2010



h. The relationships between the CO_2 emissions of the five sectors in 2011 and the areas of the industrial zones, the commercial zones, the residential zones, the agricultural zones and the transportation lands in 2010

Fig. 8. (*continued*)

Fig. 6 further reveals the profiles of the distributions of CO_2 emissions form the southwest of the Taipei metropolitan area, through center city, northeast of the metropolitan area. The distributions of the CO_2 emissions of the manufacturing industry sector are highest in the southwest and decreased toward the center of the Taipei metropolitan area. On the contrary, the distributions of CO_2 emissions of the transportation sector and the housing sector increased from the periphery of the study area to the center city. From the profile, the center city has the highest total CO_2 emissions (Fig. 6e). Furthermore, the distributions of *per-capita* CO_2 emissions are shown to have negative correlation with the population density in the Taipei metropolitan area.

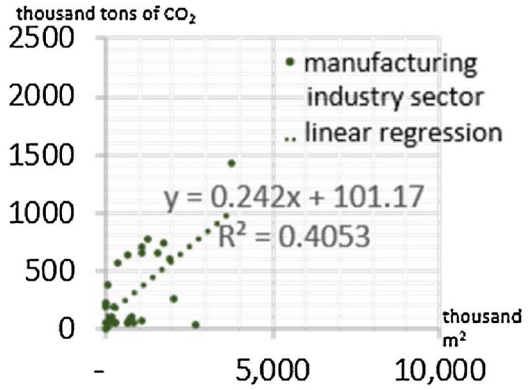
5. Relationships between development intensity, zoning areas, and CO_2 emissions

A comparison of the distributions of the total CO_2 emissions with the locations of the urban planned zones in the Taipei metropolitan area indicates that the total CO_2 emissions in 1981 were concentrated in the center of the Taipei metropolitan area where the urban planned zones were delineated. To detect how urban spatial planning had influenced CO_2 emissions in the Taipei metropolitan area, this section examines the relationships among CO_2 emissions, urban development intensity and land use types in the urban planned zones.

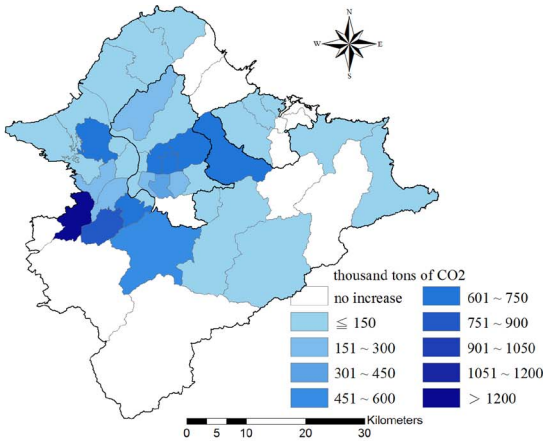
5.1. The relationship between development intensity and CO_2 emissions

The total population of the Taipei metropolitan area rose from 4.96 million in 1981 to 6.9 million in 2011. Fig. 7a shows that the CO_2 emissions and the population growth in the Taipei metropolitan area are positively correlated. However, the relationship between the *per-capita* CO_2 emissions and the population density within the Taipei metropolitan area is almost negatively correlated, particularly in the high-density districts (Fig. 7b). The administrative districts with higher population density have higher emissions of CO_2, but they have lower *per-capita* CO_2 emissions than the districts with lower population density.

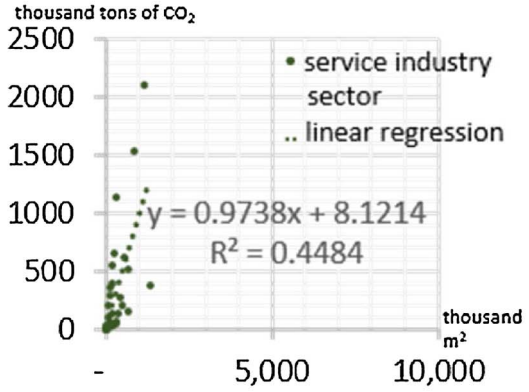
In 1981, the CO_2 emissions of the housing sector were 3,061 thousand metric tons in the Taipei metropolitan area, with no district emitting more than 300 thousand metric tons of CO_2. The CO_2 emissions of the housing sector increased to more than 2.6 times the 1981 level (to approximately 11,706 thousand metric tons) over the next 30 years. More than 40% of the administrative districts emitted over 300 thousand metric tons of CO_2 in their housing sectors. Fig. 7c presents the relationships between the CO_2 emissions of the housing sector and the population. The R^2 value increased



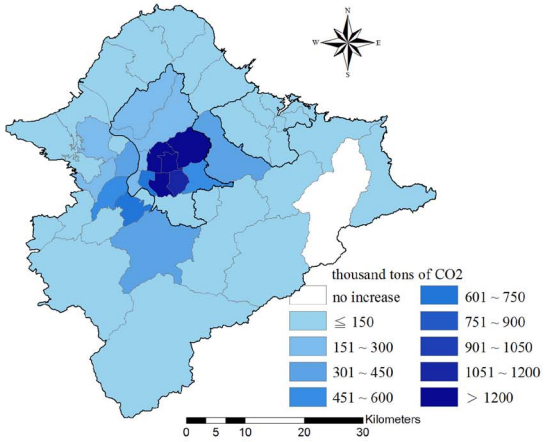
a. The relationships between the increases in the CO_2 emissions in the manufacturing industry sector during the period 1981–2011 and the areas of the industrial zones 2010



b. The increases in the CO_2 emissions in the manufacturing industry sector during the period 1981–2011



c. The relationships between the increased CO_2 emissions of the service industry sector during the period 1981–2011 and the areas of the commercial zones in 2010



d. The increases in the CO_2 emissions in the service industry sector during the period 1981–2011

Fig. 9. The relationships between the increases in the CO_2 emissions and the land use types of the urban planned zones in the Taipei metropolitan area.

from 0.5846 in 1981 to 0.9905 in 2011 Indicated that a strong and positive correlation exists between the CO_2 emissions of the housing sector and the population in the Taipei metropolitan area.

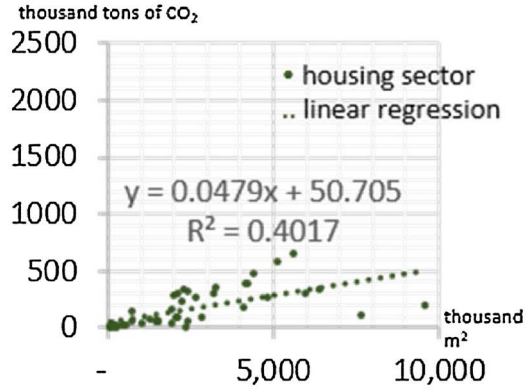
In the Taipei metropolitan area, the CO_2 emissions of the transportation sector increased from 2,967 thousand metric tons in 1981 to 12,813 thousand metric tons in 2011 (approximately 3.32 times). Only 2 administrative districts emitted more than 300 thousand metric tons of CO_2 in 1981 but this rose to 15 districts in 1995. However, the number of districts that emitted more than 300 thousand metric tons of CO_2 fell to 13 in 2006 and 12 in 2011. The *per-capita* CO_2 emissions in the transportation sector are negatively correlated with the population density in the Taipei metropolitan area (Fig. 7d). Moreover, the distributions of CO_2 emissions from transportation are evidently consistent with the transport networks, particularly administrative districts reached by Metro and the National Freeway.

The investigation on the relationships between population and CO_2 emissions indicate that CO_2 emissions from different sectors are positively correlated with the increase of urban population, which is resulted from the plan-led growth in the city. However, the urban form in the center city of Taipei is affected by urban zoning plan and is characterized as mixed use, high density and high accessibility to public transit which has helped decrease the *per-capita* CO_2 emissions in the transportation sector.

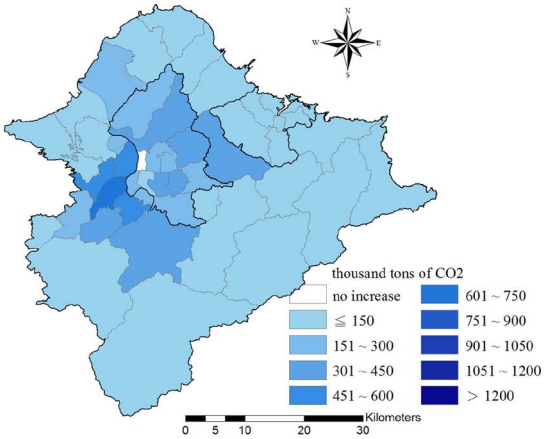
5.2. The relationship between zoning areas and CO_2 emissions

Fig. 8a shows that the distribution of the industrial zones of more than 2,000,000 m^2 in 2010 is concentrated in the western and eastern parts of the Taipei metropolitan area. The CO_2 emissions of the manufacturing sector of each administrative district in 2011 are positively correlated with the areas of the industrial zones in 2010 with larger industrial areas have higher CO_2 emission levels (Fig. 8b). The CO_2 emissions of the manufacturing sector in 2011 are consistent with the distribution of the industrial zones in 2010.

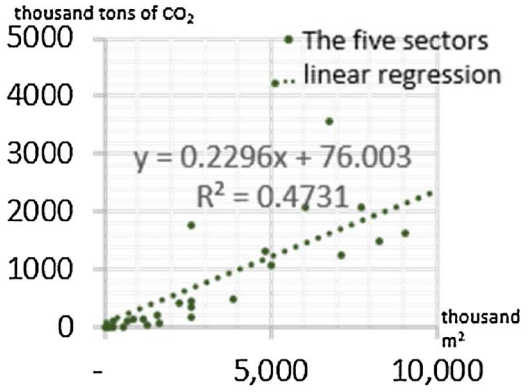
Fig. 8c shows that the areas of the commercial zones from all the districts in 2010 less than 1,500,000 m^2. The CO_2 emissions from the service industry is positively correlated with the total area of the commercial zones in 2010 (Fig. 8d). The districts with the residential areas of more than 2,000,000 m^2 in 2010 are concentrated in the west and center of the study area (Fig. 8e). Fig. 8f shows the relationships between the CO_2 emissions of the housing sector and the areas of the residential zones in 2010. These also show a positive correlation where larger residential areas having higher CO_2 emissions. Fig. 8g presents the distribution of the total areas of the industrial zones, the commercial zones, the residential zones and the transportation lands in 2010. About 40% of the administrative districts concentrated in the western and central part of the Taipei metropolitan area had areas of more than



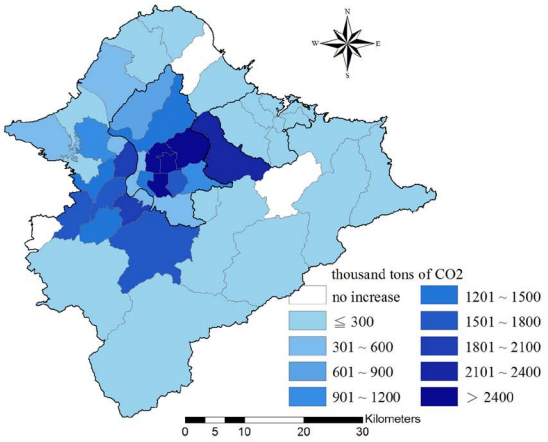
e. The relationships between the increases in the CO_2 emissions in the housing sector during the period 1981–2011 and the areas of the residential zones in 2010



f. The increases in the CO_2 emissions in the housing sector during the period 1981–2011



g. The relationships between the increases in the CO_2 emissions in the five sectors during the period 1981–2011 and the areas of the industrial zones, the commercial zones, the residential zones, the agricultural zones and the transportation lands in 2010



h. The increases in the CO_2 emissions in the five sectors during the period 1981–2011

Fig. 9. (*continued*)

4,000,000 m^2 in 2010. As shown in Fig. 8h, a positive correlation exists between the CO_2 emissions of the four sectors in 2010 and the total areas, namely the industrial zones, the commercial zones, the residential zones and the transportation lands.

In addition, the increases in the CO_2 emissions are also shown to be correlated with the areas zoned for each sector. The increases in the CO_2 emissions in the manufacturing industry sector from 1981 to 2011 are positively correlated with the areas of industrial zones (Fig. 9a). Fig. 9b displays the distribution of the increases in the CO_2 emissions in the manufacturing industry sector, which is consistent with the distribution of the areas of the industrial zones in 2010. Seven administrative districts have the increases of more than 600 thousand tons in the CO_2 emissions in their manufacturing industry sectors. Fig. 9c and d shows the increases in the CO_2 emissions in the service industry sector from 1981 to 2011. These do not appear consistent with the distribution of the areas of the commercial zones in 2010. That is because of the vertical mix of commercial uses in residential districts permitted in Taiwan. A positive correlation exists between the increases in the CO_2 emissions in the housing sector and the areas of the residential zones (Fig. 9e). The distribution of the increases in the CO_2 emissions in the housing sector from 1981 to 2011 (Fig. 9f) was consistent with the distribution of the areas of the residential zones in 2010. Fig. 9g and h shows that increases in the CO_2 emissions in the four sectors from 1981 to 2011 were distributed throughout the administrative zones, which had a larger total urban planned area, then zoned for industrial, commercial, residential, and transportation land uses in 2010.

The above analysis shows that the practice of urban spatial planning allocates different land uses spatially to accommodate growth and to prohibit the development in protected areas. The designated area and intensity permitted in each administrative district influence not only economic productivity, but also housing and traffic demands which lead to change the amount, intensity and distribution of CO_2 emissions.

6. Conclusion

From 1981 to 2011, the total area of the urban planned zones in the Taipei metropolitan area increased 122%, while the total CO_2 emissions of the four sectors increased 220%. Our analysis indicates that the increase in the CO_2 emissions in the study area is caused predominantly by the growth in these urban spatial planning areas. The spatial distribution of the CO_2 emissions in the study area also confirms this result. The districts with the largest increase in the CO_2 emissions from

their manufacturing industry during these 30 years are located in the middle and western part of the Taipei metropolitan area where most of the industrial zones in the Taipei metropolitan area are designated. The CO_2 emissions from the service industry sector in 1981 mainly occurred in the center of Taipei city. The CO_2 emissions of the service industry sector in the districts surrounding the center of the Taipei metropolitan area increased in 2011. We believe this is due to a vertical mixed use ordinance impacting the service industry sector in the central Taipei metropolitan area. CO_2 emissions of the housing sector in 1981 were mainly from the early developed areas of Taipei City, where the first urban plan of Taipei city was developed and implemented. After 30 years of urban planning, the CO_2 emissions of the housing sector have increased in the districts with rapid urban developments. Our downscaling analysis of the relationship between urban spatial planning and CO_2 emissions confirms that the CO_2 emissions in the Taipei metropolitan area increased as a result of the rise in the population, the urban planned zones and the development of transportation. A negative correlation exists between the population density and the *per-capita* CO_2 emissions in the study area. The relationship between the *per-capita* CO_2 emissions of the transportation sector and the population density are negatively correlated. The characteristics of urban form (high density, mixed use, and accessible to urban transit) in the urban planned zones have shown to be an effective means for mitigating CO_2 emissions.

Although spatial planning can and has played an increasingly important role in urban responses to climate change, progress on integrating climate protection into spatial planning efforts is still limited and much more needs to be done to translate these ideas into practice (Huang & Wang, 2016). Clearly, the relationship between spatial planning and climate change mitigation varies by city. What this study has shown is that an investigation of impacts of previous spatial planning efforts on current GHG emissions is prerequisite to ensuring effectiveness of proposed new spatial planning strategies to mitigate climate change. The continuing study to investigate relationships between spatial planning and GHG emissions in cities can provide insights on effects of spatial planning efforts during different stages of urban development. The relationships between the wealth of a city during different stages of development and the CO_2 emissions will also be an important subject of our future research.

Acknowledgment

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Appendix A

Table A1.

Table A1
The equations and the data sources of the downscaling analysis.
Source: Wang et al., 2016.

Sectors	Equations	Sources of data
Manufacturing industry, transportation and service industry	$C^t_{ik_{MTS}} = \sum_{n^t_{MTS}} \sum_{m(n)^t_{MTS}} \left[\left(\frac{E^t_{ikn_{MTS}} \times R^t_{knm(n)_{MTS}}}{p^t_{m(n)}} \right) F^t_{m(n)} \right]$ $C^t_{j(i)_{MTS}} = \sum_{k_{MTS}} \left[\frac{\sum_i C^t_{ik_{MTS}}}{D_{k_{MTS}}} \times \frac{V^t_{j(i)k_{MTS}}}{\left(\frac{\sum_{j(i)} V^t_{j(i)k_{MTS}}}{B_{k_{MTS}}} \right)} \right]$ where i is the county; t is the year; k_{MTS} is the sector; n^t_{MTS} is the energy cost n in the year t; $m(n)^t_{MTS}$ is the energy m of the energy cost n in the year t; $C^t_{ik_{MTS}}$ is the quantity of CO_2 emissions of the registered address of the sector k in the county i in the year t; $E^t_{ikn_{MTS}}$ is the amount of the energy cost n in the sector k in the county i in the year t; $R^t_{knm(n)_{MTS}}$ is the proportion of the energy $m(n)$ of the energy cost n in the sector k in the t and $\sum_{m(n)} R_{knm(n)}$ is equal to 1; $p^t_{m(n)}$ is the price of the energy $m(n)$ in the year t; $F^t_{m(n)}$ is the emission factor of the energy $m(n)$ in the year t; $j(i)$is the district j of the county i; $C^t_{j(i)_{MTS}}$ is the quantity of CO_2 emission in the district j of the county i in the year t; $D_{k_{MTS}}$ is the proportion of the total quantity of CO_2 emissions of the registered address of the sector k of Taipei City, New Taipei City, Keelung City and Kaohsiung City in Taiwan in 2011; $V^t_{j(i)k_{MTS}}$ is the value of production of the sector k in the district j of the county i in the year t; $B_{k_{MTS}}$ is the proportion of the total value of production of the sector k of Taipei City, New Taipei City, Keelung City and Kaohsiung City in Taiwan in 2011.	Industry, Commerce and Service Census; The Report on Input-Output Tables; Energy Balance Sheet of Taiwan; Taiwan Energy Statistics.
Housing	$C^t_{j(i)_H} = \sum_{n^t_H} \sum_{m(n)^t_H} \left[\left(\frac{h^t_{j(i)} \times E^t_{j(i)n_H} \times R^t_{nm(n)_H}}{p^t_{m(n)}} \right) F^t_{m(n)} \right]$ where i is the county; t is the year; $j(i)$ is the district j of the county i; n^t_H is the energy cost n in the year t; $m(n)^t_H$ is the energy m of the energy cost n in the year t; $C^t_{j(i)_H}$ is the quantity of CO_2 emission in the district j of the county i in the year t; $h^t_{j(i)}$ is the quantity of household in the district j of the county i in the year t; $E^t_{j(i)n_H}$ is the NT dollar amount of the energy cost n in the district j of the county i in the year t; $R^t_{nm(n)_H}$ is the proportion of the energy $m(n)$ of the energy cost n in the year t, and $\sum_{m(n)} R_{nm(n)}$ is equal to 1; $p^t_{m(n)}$ is the price of the energy $m(n)$ in the year t; $F^t_{m(n)}$ is the emission factor of the energy $m(n)$ in the year t.	Report on the Survey of Family Income and Expenditure; Taiwan Power Company Statistics Yearbook; Energy Balance Sheet of Taiwan; Taiwan Energy Statistics.

(continued on next page)

Table A1 *(continued)*

Sectors	Equations	Sources of data
Agriculture	$C^t_{ik_{Ag}} = \sum_{n^t_{Ag}} \sum_{m(n)^t_{Ag}} \left[\left(\frac{E^t_{ikn_{Ag}} \times R^t_{knm(n)_{Ag}}}{p^t_{m(n)}} \right) F^t_{m(n)} \right]$ $C^t_{j(i)_{Ag}} = \sum_{k_{Ag}} \left(C^t_{ik_{Ag}} \times \frac{A^t_{j(i)k_{Ag}}}{\sum_j A^t_{j(i)k_{Ag}}} \right)$ where i is the county; t is the year; $j(i)$ is the district j of the county i; k_{Ag} is the sector; n^t_{Ag} is the energy cost n in the year t; $m(n)^t_{Ag}$ is the energy m of the energy cost n in the year t; $C^t_{ik_{Ag}}$ is the quantity of CO_2 emission of the sector k in the county i in the year t; $E^t_{ikn_{Ag}}$ is the NT dollar amount of the energy cost n of the sector k in the county in i the year t; $R^t_{knm(n)_{Ag}}$ is the proportion of the energy $m(n)$ of the energy cost n in the sector in the year t, and $\sum_{m(n)} R_{knm(n)}$ is equal to 1; $p^t_{m(n)}$ is the price of the energy $m(n)$ in the year t; $F^t_{m(n)}$ is the emission factor of the energy $m(n)$ in the year t; $C^t_{j(i)_{Ag}}$ is the quantity of CO_2 emission in the district j of the county i in the year t; $C^t_{ik_{Ag}}$ is the quantity of CO_2 emission of the sector k in the county i in the year t; $A^t_{j(i)k_{Ag}}$ is the area of the sector k in the district j of the county i in the year t.	Agricultural Statistics Yearbook; Forestry (Logging) Production Cost; Fisheries Statistical Yearbook of Taiwan, Kinmen and Matsu Area; Taiwan Power Company Statistics Yearbook; The Report on Input-Output Tables; Energy Balance Sheet of Taiwan; Taiwan Energy Statistics; Car statistics.

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